BUILDING ENERGY SYSTEMS AND AUDITING

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Week - 01

Lecture - 02

Lecture 02: Thermal Properties of Material-I

So, good morning. Today we will start lecture number two on module number one. So, initially we have an introduction module in which we are going to talk about some of the introductions to building physics. We will start the physics portion today, the thermal properties of matter that I will discuss in the consecutive two lectures. So, in this particular lecture number two, I am going to cover the heat transfer mechanism, conductivity and the transmission and the transmittance of the the heat and also the periodic heat flow.

So, if you see the flow pattern or the heat transfer in a building, it mainly occurs in three ways. The first one is called conduction, which is a kind of flow of heat from one point to another if there is a temperature gradient. What is a temperature gradient? There should be a differential temperature existing from one layer to another layer; otherwise, heat will not transfer. Now, in this particular case of conduction, the heat will be transferred through a solid medium and it will be transferred from one layer of particles to another layer of particles, and then to a third layer of particles, and so on.

So, by virtue of this particular movement, you require a solid medium, and that is called conduction. So, all the materials that exist on this earth, and some of them that we are using for buildings, actually exhibit the conduction of heat. The second process is called convection of heat, which actually talks about the transfer of heat or the movement from one point to another. Again, it involves a temperature gradient, but this will be through fluid molecules. Fluid molecules include two types of fluids: one may be a gaseous medium, mostly air in our case, or sometimes it may be water or any kind of liquid medium.

So, any kind of heat exchange through the window because of the natural ventilation or any kind of heat exchange process inside the building because of the air conditioning and all is actually or maybe you just run a fan, ceiling fan, or maybe a stand fan, it is a kind of convection of the heat from one place to another because of the change of air from one point to another and carrying out that heat. The third one is called radiation. Radiation is a process where you do not need any kind of media.

Basically, it is the propagation of heat through electromagnetic waves. Actually, heat is an electromagnetic wave. And it has a kind of frequency or wavelength band. So, suppose from the sun, the heat comes to the earth, and there is a lot of space available where there is no air, nothing is there, but still, we get the heat because of this electromagnetic radiation, which is radiant energy that comes from the sun to the earth.

So, any hot object actually placed inside a room, maybe it is a very hot wall or maybe a very hot window or maybe some kind of instrument, maybe a heater. So, from there, the heat actually may transfer from one point to another through radiation. Radiation and if, suppose, I imagine that particular room does not have any air, still that particular energy will propagate from one point to another. So, now let us see.

So, these are the one of the basically a conceptual picture that from the all the envelop surfaces which is actually The solid surfaces the conduction will take place, the radiation will take place and then from the solar radiation the it is comes through the window or maybe any kind of glazing or any kind of the skylight from there the radiation can come in. the convection can come through maybe through window or maybe some kind of the openings in the the the envelope. So, from there the convection and then it can get lot of the heat gain will be there in the particular building inside. We will now talk about some thermal conductivity because this is one of the very important things that we will take into we should take into account when we going to model any kind of building and when we go for some kind of assessment of some kind of the.

So, maybe we can see the initial the fundamentals physics of this thermal conduction. It is actually mathematically following a law called Fourier's law Fourier law sorry. This law stated that the the heat flux that is I have denoted as $q_\chi = - k \, dt/dx$. Actually, if you see this is the $q_\chi \propto dt/dx$ This dt/dx is the this is the thermal gradient that there is a kind of a external temperature and internal temperature or the two temperature both the side of a particular object exist and there is a differential temperature exist.

this is the there is a differential temperature exist and this the x the change of the the length is this one this length is the l. So, it is depended upon the how thick it is or how thin it is and also the how much is the differential level of the temperature difference between the two surfaces. It is actually going to say that this kind of law is also exist in the the electrical electricity then where there is a voltage drop voltage exist there is a voltage difference exist there should be a pass of current. If there is a height difference exist there will be a pass of the flow of water is exist in a through a pipe. So, those are the some of the cases which can actually replicate with the thermal conductivity Fourier law equation and finally, it has to have some constant called the k or it is called the k value thermal conductivity of the material which is a unique property of the material which denotes in watt per m² ° centigrade.

Something like the density is a very unique property. Something like the specific heat is a very unique property. Something like the expansion coefficient, that α value of a material, is a unique property. This k is also a very unique property of a material. So here, just as I told you, this dt/dx can be replaced as T2 - T1, which is the differential temperature. And if this is 0, that means there is no differential temperature, so that means both are equal, and there will be no heat passing through from one end to the other. And that divided by L, the thickness of the object, and $q_\chi = k(T1 - T2)/L$. Now here, if I multiply this q_χ by A, because q_χ is the heat flux, it is W/m², as we all know. In the first lecture, we discussed that the watt is the rate of energy passing from one point to another, which is joule per second.

So, per m² area, per m² area of the envelope or maybe any object, how much heat is passing through per second, that is your heat flux, that is your q. Now, if I multiply that q_χ by A, which is the total area instead of the 1 m² area, the whole area, if I know the what is the width of that object, what is the height of the object, or length or height. So, I know that particular area, that particular area, how much total heat is actually entering by the conduction method, and this q_χ, capital Qx, will be in what because I have already multiplied by the m², ok. So, if I multiply with k_χ, then it will be a watt.

So, this is the first fundamental that we should understand. We have developed a material property or understood a material property like the k value, which is also called the k value. This thermal conductivity will come into that. So, what I have written here is that the conduction of heat through a body can be seen in the spreading of the molecular movement from one point to another. And this particular, how fast that particular heat can be conducted from one point to another, how quickly or how slowly, depends upon that

particular k value. Suppose you keep both T1 and T2 at the same temperature difference, maybe 10° or 20°, whatever it is, whatever it may be, and you keep maybe 1 centimeter thick or some unit amount of thickness of the material. All the materials will exhibit different types of heat conduction, and qx will be different. So, some of the materials will have a very high value, some of the materials may have a high value, like almost 400 W/m²°C.

So, it will actually allow 400 watts, 400 J/s per meter thickness if there is a drop of 1 ° centigrade. But some of the materials will be very, you can say, insulative materials, having very, very low, almost 0.03 watts per meter of thickness and per ° centigrade of the temperature difference. So, those are the insulative materials like wool or maybe some expanded polystyrene or those kinds of materials, whereas the metals show almost like 400 or more than 400 sometimes. So, that is the very unique value that the thermal conductivity, we call that value as the K value.

So, please remember this K value has a unit of watts per meter per ° centigrade. So, per unit of thickness, if there is a 1-° temperature difference, how many watts, how many joules per second the energy is transmitted, instead of transmitted, I must say it is how much is conducted from one point to the other. So, I have listed down some of the K values of some materials: plaster is 0.5, whereas you see if it is granite, it is 2.3, you see this is 2.3, brick is 0.7, whereas if you see the air, air is 0.05, it is a very, very insulative kind of material, EPS, expanded polyurethane, something like thermocol, a hard kind of thermocol, is almost 0.035 like that. And also, I have listed down the density values, also I have listed down the specific heat value, those will actually be required afterward. So, these are some of the recommended values of the materials which we usually use in the building.

Concrete has 1.33, the glass is having 1.1 watts per m² ° centigrade. So, now we do an example: suppose a wall is made of two such materials and the K values are mentioned, the first layer, the right-hand side layer, is 200 mm thick and the second one is 100 mm thick, and the K values are 0.5 and 1.5. And, on one side, the temperature is 40° centigrade and the other side is 20° centigrade. So, there exists a temperature gradient. So, my question is, how much will the temperature be at this particular junction, and how much will the heat flux be if I want to solve this?

So, I know the heat flux will be the same because heat cannot be In a particular steady-state situation, heat will be whatever heat comes in one side that will actually go to the

other side, right? In the case of a steady-state situation, initially, it will not show like that because some of the heat will be absorbed by the layers, and there will be some kind of changes. So, by virtue of the continuity equation. So, if I say that q1 is the gradient from the first layer.

So, I have written down that $(T1 - \theta)/b1$. So, b1 I have replaced this L; if you remember, the equation is Q equals K multiplied by $(T1 - T2)/L$. So, here I have the first layer; the right-hand side layer on one side is T1. And on the other side, at the junction, it is θ, and the thickness is b1. The second layer, the left side layer, has θ, T2, and there is a b2; the thickness is different. So, now, I replace all the values, and I know q1 must be equal to q2 because of the continuity, and I can solve for θ. Everything I know: I know b1 is 200 mm, b2 is 100 mm, but I have to put the b1 and b2 values in meters, not in other units.

And K1, K2 is also given to me: 0.5 and 1.5. T1 I know, T2 I also know: 40° and 20°. So, everything is there; only θ is not there. So, I can solve for it and I can find out that θ is almost about 22.85°, and just replace the value of θ in one of the equations; I can say that the heat flux is almost about 42.8 watts per square meter. So, like now, like that, if I add up, because you know, in reality, in building envelopes or maybe anywhere in the roof, also maybe in the floors, we have two or three different types of material; we may have a brick layer So, we must have some kind of plaster, minimum, or maybe we have a cavity wall, or in the roof, we may have an RCC roof, and over that, we may have some kind of protective waterproofing layer.

So, there are two or three layers of material. So, through that, they have different K values. So, it should exhibit in this way. So, this is what happened in that particular scenario when there is a different type of material. Suppose, these are two layers of brick, and in between there is an insulative layer.

So, something like this is your hollow block, and there is an insulative layer. So, each layer will have its own K value, and each layer will have its own differential thicknesses. So, based on that, a composite conductivity or composite value will be derived from that particular combination, which is called the transmittance value, which is further very important in the sense, The K value is very basic, but I want to use this transmittance value, or it is very popularly called the U value. So, that will be readily available to me, and I will actually use that particular value for any kind of heat load calculation or cooling load calculations.

So, otherwise, I have to go through the layer-by-layer calculation with the K value every time. In that, the composite U value is supposed to be, what is the formula or what are the equations? So, you see, this is one of the cross-sections of a wall I have shown, and it has two materials: suppose there is a red-colored material and there is another colored material. So, there are two materials that have different K values: maybe it is your brick, your plaster, or maybe you have an air gap.

So, those are there and there are having different thicknesses b1, b2 like their different thicknesses and you see this particular that the wall will have some surface resistivity. And the surface resistivity which will try to protect the heat to conduct and that depends upon lot of things that depends upon the the the the the the the color of the particular wall that particular the the texture of the wall and what is there is a film of air will be there in the the both the the the the wall side. So, based on that there is a resistance in the outside and the resistance in the inside. So, based on this Rso that is I am I am calling that as a resistance surface outside resistance of the surface inside and

I include these actual values of the material K and the and the thicknesses, then the U value can be calculated based on this particular formula. So, it is 1 upon the inverse of K and multiplied by the B. So, if this 1 upon K is sorry 1 upon K is called the resistivity So, I multiply with the b into k that b is the thickness and this is for the first layer second layer like that. So, b2 by k2 like that and I add this is a resistivity. So, I can directly add Rso + Rso. So, I got the whole resistivity of the whole layer. So, it is the kind of the equivalent resistivity of the layer and if I am reciprocal, I am getting the reciprocal of that to get that particular the transmittance value. So, this this value is called this reciprocal value is called the Ra to a, a to a means air to air that means, outdoor air to the indoor air is this value, but this Rso and the Rsi is very very small. So, sometimes we ignore.

So, if we want to ignore it, then I can also write this U value as something like 1 upon this 1 upon R, sorry not R, this will be b1/k1 + b2/k2 + … like that. So, I can stop that to this without taking the air to air, but because this will be very negligible, but sometimes we can add it. So, in that we can, and this particular value is called the U value and the transmittance value that it has a unit of watt per m² ° C. Please remember, the K value has the unit of watt per meter per ° C. Now, it is watt per m² per ° C, that means, per square meter how much watt. So, just if I multiply with the amount of area, I can directly get, and if I multiply with how much is the temperature difference, I can directly get the heat flux.

or the total heat that will flow from one point to the other. So, let us calculate, suppose I have a typical brick wall 150mm thick brick which is having a K value of 0.7, this is the thick 20mm thick plaster of K value of 0.5. 12mm of plaster on another side and that is 0.5 again. So, as per my and those things are the Rso and the Rsi values are the mentioned over here, and this is a kind of constant value; it also changes, but we can say this is a constant for our calculation. And then I am going to use this equation; this has three layers.

So, there will be b1/k1, which is your first one, if you see this is your Rso. So, this is your this, and this is the last one is the 0.13 is the Rsi which I have mentioned here and here, and this three is the in the middle three. So, first one this is your 20mm thick and this is 0.05 for the plaster. This is your 115mm thick, I have to transfer it to meter, and this is your brick, and this is your again 12mm plaster, and this is your K value of the plaster.

So, by doing that, we can finally find out that the U value is 2.51. So, we add up, and then again, we make this kind of the reverse reciprocal of that, and we can find out that the U value is 2.51. So, we may say that a particular brickwork, having 150mm thick and plaster on both sides, 20 and 12. will have a U value of 2.5 watts per m² ° C. So, that means, if there is a 1-° temperature difference and then if there is a 1-m² of the area, if I see it, it will transmit almost about 2.51 watts. If there is a 2-° difference, then it will be almost 5 watts, double of that.

If there is a 2m² and 1-° difference, again, it is 5. So, like that, we can just multiply with the area and the temperature difference between the two sides, and we can find out this. So, I have calculated for a 5inch brick wall. which just now I have calculated as 2.5 or something like that. I have also calculated for the 10-inch brick wall, just changing the value, this value, the millimeter value, as point instead of the 115 to 250.

So, the U value is reducing. U value reducing means, it is less, I mean, it is stuff to penetrate; the transmission is very, very low compared to the 5-inch wall or so. So, that will be required for much, that will give you much more protection from the heat also. So, I have an excel sheet. I will show you, and so I have given three layers, and that particular table I have mentioned over here.

So, in this Excel sheet, we can calculate the U-value of the composite wall. A maximum of 3 different layers can be taken into account, and their corresponding K-values can be marked in yellow. So, suppose if I go with some kind of, instead of, hm, this is 0.35. Suppose I am going with some kind of plaster on one side; plaster is having 0.5. 0.5 over

here and a 250 wall, and there is a 25mm thick, 25mm thick, this is your U, this EPS, that is this thing. So, the U-value is 0.9, okay.

See, if I suppose instead of the 1 inch, that is 25, instead of that, if I put 50 mm, this thing, the EPS, that is the insulative thing, it is again going to reduce to 0.55. So, I will share this with you, and you can actually go through this. So, there are different E-values. So, smaller E-values are very good, right? Because it will be very good in the sense of protection from heat or so. So, you see, the brick cavity with a 5-inch brick cavity and the, sorry, the 3-inch air cavity with the.

So, a 3 inch air cavity with two layers of brickwork of 5 inches and 10 inches, it is almost 0.27, whereas, you see, if it is only 10-inch brickwork, it is 1.7 almost. And the maximum one may be the 6 mm glass, which is 5.7. So, which is your U-value. So, the U-value will definitely be better; the lower the U-value, the better, because that will conduct less amount of heat, and it will require, I mean, that will actually give us less amount of heat load or cooling load.

So, as I told you, we can find out this Q by just multiplying the area of the wall. or the envelope with the corresponding U value, suppose it is brickwork or your cavity wall, whatever, and the ΔT. ΔT is your temperature difference, which means the temperature difference between the outdoor and the indoor. So, if you take the average outdoor temperature as 35° and you want to keep the indoor temperature as maybe 20°. So, there is a difference that 35 - 20 or whatever it is. So, suppose I have another example.

So, I have a wall area of 40 square meters and an indoor area of 10 square meters. The outdoor and indoor temperature difference is 18°C. I am keeping 18° lower inside, and the outdoor temperature is higher. The U values are 1.5 and 3. Then, I can calculate in a straightforward manner what the amount of Q is, which is how much heat. through this conduction. So, I have multiplied 1.5, which is the U value of the wall, and 40, which is the area, and 18, which is the temperature difference. This is for the window. The window area is 10, and this 3 is the U value of the window, and this is again the temperature difference because it is the same outside and inside.

So, I can add and then this is the. I can have another kind of solution where I can find out the average U value. So, multiplying the U value of the wall and the area of the wall + the U value of the window and the area of the window, and divide that by the total amount of the area, which is 50 square meters, and I get a particular average U value of the wall as 1.8 watts per square meter per ° C, and then I just multiply this 1.8. is the average U

value. The total area is now 50, the 10 + 40, and this is your 18, which is the temperature difference. The same value I will get for that. So, specific heat is another thing that will actually come into play where we can define the specific heat as the heat that is required to raise 1 ° temperature of 1 kg of that particular object or any matter or any material.

So, that means, to increase the temperature by 1 °, how much heat does it store or is required? So, the specific heat is very high. So, you need more heat to actually put in and raise the temperature by 1 °. So, the high specific heat material will definitely give you better heat storage capacities. So, from that point of view, we can come to a particular concept of thermal mass, where this thermal mass is nothing but the product of this mass multiplied by the specific heat.

So, the heat energy, how many joules are required to increase a temperature ΔT. So, suppose ΔT, let us suppose 1 °, and you have 1 kg of a thing. So, multiplied by the specific heat. So, that much amount of heat will be required. So, this increases the temperature, and if you do not increase the temperature, the temperature will not be conducted from one point to the other.

Because there should be a differential temperature existing in the layers of the thick brick wall or so, and then it will be transmitted from one point to the other. So, that is why this thermal mass is very important to see that heavy thermal mass will store more, and less thermal mass, lightweight and all these things, will store a little less. So, here when we see another kind of property called thermal diffusivity, we see if these three things come together. The thermal conductivity, the K value, is a very fundamental property of a material. Density is another fundamental property; density gives you how much the weight and all these things; the same volume, high density will give you more weight and specific heat.

So, if the thermal conductivity is high, the rate will be faster; the faster rate will transmit from one point to another, from one layer to another. The density is high; it will be slower because the material has more weight. So, it will store more energy, more heat, and the specific heat, if it is high, again it will be slower because high specific heat means to raise 1 ° temperature requires a lot of joules of energy or a lot of joules of temperature. So, from that point of view, if you see, we if you have a kind of another equation or maybe another kind of property, we can derive that K divided by this d by C; it should be d not d to be rho. I will change it to rho. So, then this is called the thermal diffusivity; see, the K by rho into C that means, if it

The k value, it is thermal diffusivity, is increasing where if the rho and C drop, it will increase the thermal diffusivity. So, high thermal diffusivity means it will be very fast; the heat will transmit from one layer to the other; it goes very fast. So, that of what I have discussed, the high thermal conductivity, high thermal diffusivity, density multiplied by specific heat, that product also in the thermal mass, what we have discussed, and that also goes with the high amount of diffusion or whatever. So, these are some of the building materials; the K value, density value, and the specific heat value are mentioned, and I have calculated the thermal diffusivity. You see, the highest comes over here; the concrete has very high diffusivity, very high, which means it will be very fast; the rate will be such that the temperature or the heat will be absorbed in the layers and layers and layers, and then it will go.

If you see the lowest one, again it is the EPS, that is the expanded polystyrene; it will be very slow; it will heat up one layer and then it will go to the next layer; almost almost 6.6 times, no 60 times, maybe not 6 times. So, now you see the periodic heat flow; there are fluctuations of the heat in 24 hours temperature. So, it will store heat in one point and then it will release it to the next, the inside. So, there is a temperature, the heat, the temperature difference in the outside and the temperature difference in the inside, which can be shown like this: the black color curve, it is a kind of periodic curve. This periodic curve is definitely having kind of changes in the different seasons, but in a particular season, it will be periodic in nature, and this red color one is the indoor temperature curve.

So, there is a peak difference, and there is a shift of the peak also. So, maybe at a particular time, maybe around 12 or not 12, it is maybe up. At 2 PM, the peak is there in the outdoor temperature, but my peak in the indoor temperature is almost about maybe 9 PM or so, like that. So, there is a difference in this. So, this difference has been countered by, or there are two parameters taken out: one is the time lag or the phase shift, which is how much the difference is from 2 PM to 9 PM, or how much, 7 hours or whatever.

And another one is the decrement factor, which is the amplitude attenuation, that is, how much is the Ti maximum and the Tii maximum. These two are taken care of. So, the impact of the thermal mass, if I have a very low thermal mass. So, that peak attenuation of the amplitude will not be so much. So, it will have a very

less amount of time lag also because within one hour or less hours, it will be actually the time lag or the peak will be there, and this very high decrement factor whereas, if it is a

kind of the high thermal mass material, then it will be the reverse way: it will be very flat, and it will have more time lag and a low decrement value. So, I have the relation between the time lag and the wall thicknesses. If the wall thickness increases, the time lag increases, okay, and because of the different types of densities, the time lag also increases.

And in another way, if the wall thickness increases, the decrement factor decreases because of the insulation outside, insulation inside, and the uninsulated case. It will also be going to have changes. So, it is always better to have outside insulation, as it gives you a better kind of decrement factor in such scenarios. So, that is all for today's lecture, and these are my references. So, what we have done over here is we discussed the K values and the U values,

which are very major factors that play a role in the heat gain or heat loss calculations of a building. We also discussed the temperature variations outside and inside, the phase lag, and the amplitude attenuation. Thank you very much.